InP Nanowire lasers Epitaxially Grown on (001) Silicon ‘V- groove’ templates

Bin Tian[1], Zhechao Wang[1], Marianna Pantouvaki[2], Weiming Guo[2], Merckling Clement[2], Joris Van Campenhout[2], Dries Van Thourhout[1]

[1]: INTEC Department, Ghent University, Sint-Pietersnieuwstraat 41, Ghent 9000, Belgium

[2]: IMEC, Kapeldreef 75, 3001 Heverlee, Belgium

e-mail: bin.tian@intec.ugent.be

Abstract— **In this work, we demonstrated an ultra-low threshold nanowire laser that is monolithically integrated on (001) silicon substrate. By using a V-groove template, we were able to reduce the laser threshold one order of magnitude (0.19pJ per pulse) compared with the last generation, and the yielding throughout the sample has also been increased dramatically.**

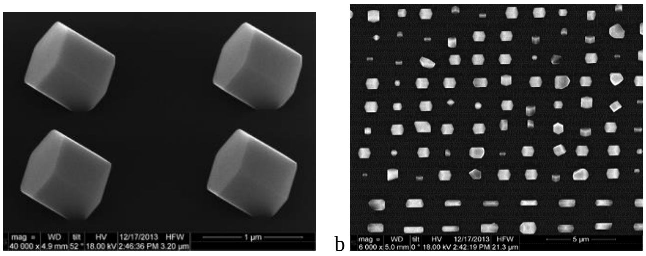
I. INTRODUCTION

Silicon photonics have been proven to be an outstanding platform for telecoms since it was introduced nearly a decade ago. Nowadays silicon photonics draws more attentions because of its excellent potential on bio-sensing and other non-linear applications. Due to its indirect bandgap, wherever an on-board light source is required, III-V materials are routinely introduced. Generally speaking, III-V compounds are efficient gain mediums that are the main material platform for active optical components in the past few decades.

The traditional integration methods to combine the III-V devices and the silicon substrate, e.g. flip-chip [1], wafer bonding [2-4] and stamp print technics [5], have been investigated for almost a decade world widely. Currently, they still suffer from the poor heat sinks, the non-standard process flow, and the corresponding performance and cost limitation. In order to achieve highly compacted integrated lasers with better performance (good heat dissipation, lower power consumption, and lower cost), selective area epitaxial growth has been proposed. As one of the most used platform for telecom bands optical components, InP has a 8.1% lattice mismatch compared with silicon, which sets the obstacle for high quality InP growth on silicon. Several solutions have been put forward recently to annihilate the thread dislocations and anti-phase boundaries (APB) [6-8]. Previously we reported a polytypic InP nano-cavity laser which is epitaxially grown on (001) Silicon [9] by using step-surface-Germanium seed layer to eliminate the anti-phase boundaries (APB) [10], however, only very limited amount of lasers had been found. In this work, we present the further improved yielding of nanowire growth and material quality by using ‘V-groove’ templates [11], in which nucleation of InP in trenches has been improved [12], and APBs can only form at the trench corners which will be blocked by burring the corner before heteroepitaxy.

II. FABRICATION

To prepare the V-groove templates, standard shallow trench isolation (STI) process was firstly carried out to form the designed trenches on a (001) silicon wafer. The subsequent wet etching process by using a 5% TMAH solution at 80^{o}C was utilized to form the V grooves at the bottom of the STI trenches. Prior to the epitaxial growth, the wafer was etched by HF to remove the native oxide layer, and was then baked in H_2 at high temperature for 10 minutes to desorb the surface contaminants. During the cooling down, tertiarybutylarsine (TBAs) was introduced to passivate the {111}Si surface. The main growth would be performed in two steps by metal−organic vapor phase epitaxy process (MOVPE). A low temperature growth is used to form the stable InP nuclei while the following high temperature growth to obtain high crystalline quality epilayer. Figure 1(a) shows a typical scanning electron microscopy image of the InP nanowire that is grown on top of the template. The hexagonal outer shape and the uniform tilted angle with respect to the sample surface prove that these are typical InP nanowires inclining to the [111] crystalline direction. Regarding the improved yield compared with our previous work [9], Fig.1 (b) shows a typical SEM image of the sample surface. By a simple count, there are around 35 out of 80 sites that successfully form the nano-laser cavity, and this ratio can be applied to most parts of the sample.

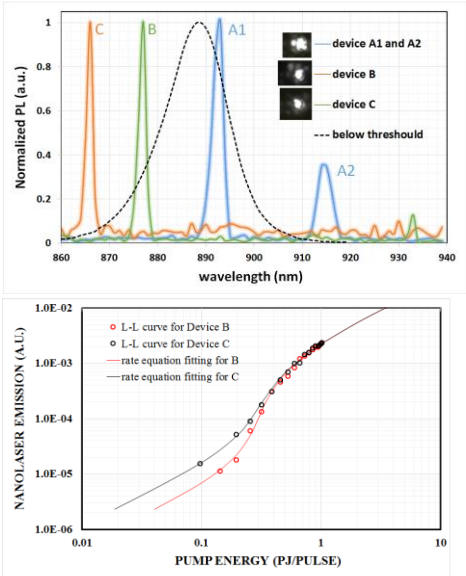


a b

Figure 1. a) A tilted SEM picture, we can find that for those pillars which have similar shapes, also have similar dimensions, such as diameters, lengths and tilted angles. b) A top view of random location from the sample by SEM. To be noticed here that the last two rows at the bottom are from another mask, which are not included here.

III. CARACTERIZATION RESULTS

The optical characterizations of the grown InP-on-Si nanowires were performed on the micro-photoluminescence (PL) setup which has two alternative pumping sources: a continues wave (CW) laser working on 532nm with a maximum output power of 1.5W, and a Nd:YAG nanosecond pulsed 532 nm laser with 7ns pulse width and 259Hz repetition rate. A ×50, 0.6 numerical aperture (NA) objective was used to deliver the pump light while the light collection was realized by the same



a

b

Figure 2. a) The solid lines are normalized PL of different devices, for device A1 and A2, they are too close to be separated. The dash line is the normalized PL under the threshold, pumped by CW laser. b) The L-L curve of device B and C respectively at room temperature. The circles are measured points and the solid curves are the rate equation fittings, from which the threshold are derived for both devices, B at 0.21pJ and C at 0.19pJ.

objective. The PL signal was resolved by a 1/4 m monochromator with TE-cooled silicon detector. For wide area PL measurement, the diameter of the pumping area is around 20μm, while for single laser characterization, the pumping spot diameter was reduced to 3μm, with the pumping intensity remained the same.

APB free III-V material grown on Si(111) surface has been evidenced by several groups already, however, twins and stacking faults are still inevitable in most cases [7-8]. The characterization results of single pillar under a CW pumping condition, shown as dash line in Fig. 2(a), shows that the PL peak is slightly blue shifted from the PL of pure zincblende (ZB) InP at room temperature [13]. As discussed in our previous work, this effect mainly comes from the polytypic crystal property of the nanowires, Supper-lattice liked heterostructures are formed by the close packaging of ZB and Wurtzite (WZ) InP crystal phases, and the corresponding quantum confinement effect blue shifts the bandgap . By using the ns pulsed laser for optical pumping, one notices that a good amount of the InP-on-Si nanowires start lasing. Fig. 2(a) shows the normalized PL spectra of different nanowire lasers above threshold, and the insets are the corresponding PL images.

For the laser yield, by PL characterization, we also find a dramatic increase by using the 'V-groove' template. From the PL image of a random area on the sample, as shown in Fig. 3, we can see that the working nanowires are quite dense within the 20μm-diameter area.

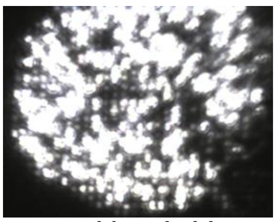


Figure 3. The PL image pumped by pulsed laser, and the diameter of the pumping area is around 20μm.

IV. Discussions and Conclusion

As shown previously by FDTD simulations [9], the optical mode that can be supported by these tilted nanowires are helically propagating modes. Although these cavities are much shorter compared with other nanowire lasers, optical modes with up to 150 Q factor can still be supported. In addition, thanks to the limited size of the cavity, only few modes can be supported in the wavelength range of the gain spectrum, and large spontaneous emission factor (β) has been achieved (0.06-0.075). This high β is essential for the laser threshold reduction.

In summary, we improved the nanowire growth yield and reduced the threshold of our nanowire laser from last work by switching to 'v-groove' templates. The device becomes much simpler to fabricate, more robust and efficient for applications, such as bio-sensing and optical quantum communication.

References

[1] Edge, C.; Ash, R.M.; Jones, C.G.; Goodwin, M.J., "Flip-chip solder bond mounting of laser diodes," Electronics Letters , vol.27, no.6, pp.499,501, 14 March 1991

[2] H.Wada and T. Kamijoh, "Room-temperature CW operation of InGaAsP lasers on Si fabricated by wafer-bonding," IEEE Photonics Technology Letters, 8, 173-175 (1996).

[3] A.W. Fang, H. Park, O. Cohen, R. Jones, M.J. Paniccia, J.E. Bowers "Electrically pumped hybrid AlGaInAs-silicon evanescent laser," Optics Express, 14, 9203-9210 (2006).

[4] P.R. Romeo, J. Van Campenhout, P. Regreny, A. Kazmierczak, C. Seassal, X. Letartre, G. Hollinger, D. Van Thourhout, R. Baets, J.M. Fedeli, L. Di Cioccio, "InP on Silicon Electrically Driven Microdisk Lasers for Photonic ICs," Optics Express, 14, 3864-3871 (2006).

[5] J. Justice, C. Bower, M. Meitl, M. B. Mooney, M. A. Gubbins, B. Corbett, Wafer-scale integration of group III–V lasers on silicon using transfer printing of epitaxial layers, Nature Photonics 6, 610–614 (2012)

[6] Wang, Z.; Junesand, C.; Metaferia, W.; Hu, C.; Wosinski, L. Lourdudoss, S. Mater. Sci. Eng. B 2012, 177 (17), 1551 − 1557.

[7] J. Motohisa, J. Noborisaka, J. Takeda, M. Inari, T. Fukui, 2004 Catalyst-free selective-area MOVPE of semiconductor nanowires on (111)B oriented substrates. J. Cryst. Growth, 272, 180-185, 0022-0248.

[8] F. Ren, K. Wei Ng, K. Li, H. Sun, Chang-Hasnain, Connie J.,High-quality InP nanoneedles grown on silicon, Applied Physics Letters, 102, 012115 (2013),

[9] Z. Wang, B. Tian, M. Paladugu, M. Pantouvaki, N. Le Thomas, C. Merckling, W. Guo, J. Dekoster, J. Van Campenhout, P. Absil, D. Van Thourhout, Polytypic InP Nano-laser Monolithically Integrated on (001) Silicon, Nano Letters, 2013, 13, 5063-5069.

[10] C. Merckling, N. Waldron, S. Jiang, W. Guo, O. Richard, B. Douhard, A. Moussa, D. Vanhaeren, H. Bender, N. Collaert, M. Heyns, A. Thean, M. Caymax, and W. Vandervorst, J. Appl. Phys. 114, 033708 (2013).

[11] M. Paladugu, C. Merckling, R. Loo, O. Richard, H. Bender, J. Dekoster, etc., Site Selective Integration of III–V Materials on Si for Nanoscale Logic and Photonic Devices, Cryst. Growth Des., 2012, 12 (10), pp 4696–4702.

[12] C. Merckling, N. Waldron, S. Jiang, W. Guo, N. Collaert, M. Caymax, E. Vancoille, K. Barla, A. Thean, M. Heyns & W. Vandervorst, "Heteroepitaxy of InP on Si(001) by selective-area metal organic vapor-phase epitaxy in sub-50 nm width trenches: The role of the nucleation layer and the recess engineering"J. Appl. Phys. **115**, 023710 (2014)

[13] Mishra, A. and Titova, L. V. and Hoang, T. B. and Jackson, H. E. and Smith, L. M. and Yarrison-Rice, J. M. and Kim, Y. and etc., Applied Physics Letters, 91, 263104 (2007)